Shallow Cumulus Convection and Its Parameterization in AM3

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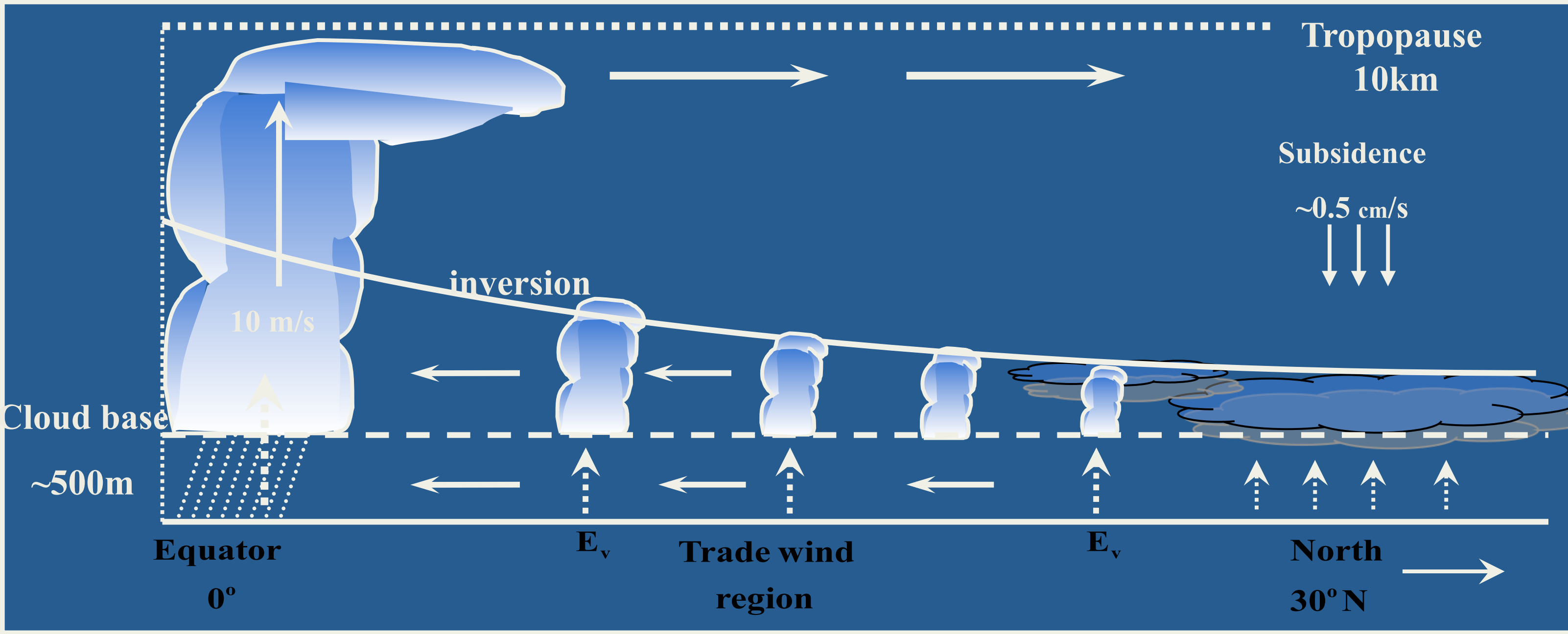
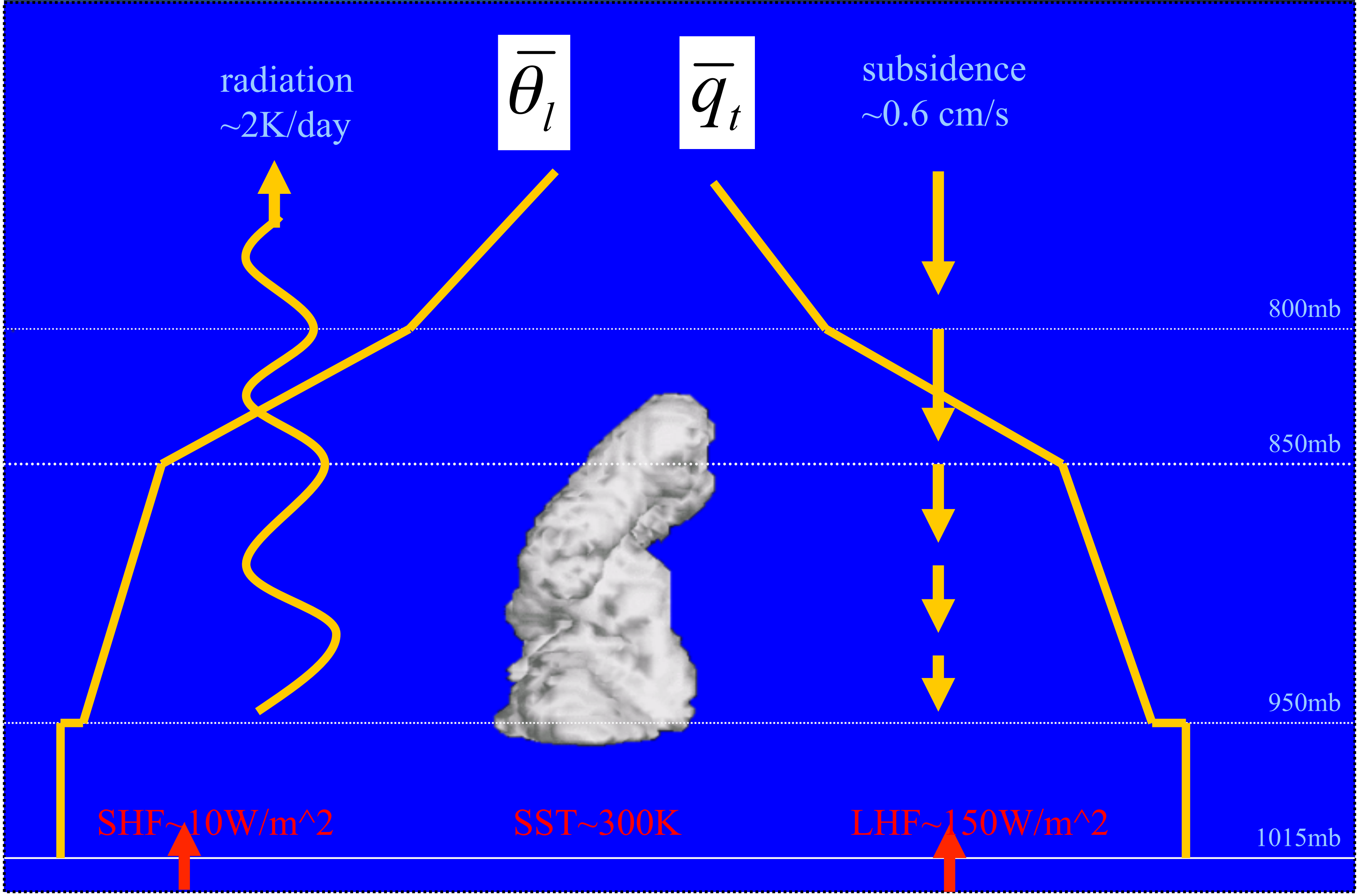
A view of trade wind shallow cumulus cloud fields

Hadley Circulation and shallow cumulus clouds
(Figure courtesy of Pier Siebesma, KNMI)



Deep Convective Clouds	Shallow Convective Clouds	Stratocumulus
Precipitation	No precipitation	Interaction with radiation
Vertical turbulent transport	Vertical turbulent transport	
Net latent heat production	No net latent heat production	
Engine Hadley Circulation	Fuel Supply Hadley Circulation	

Trade wind cumulus boundary layer physics



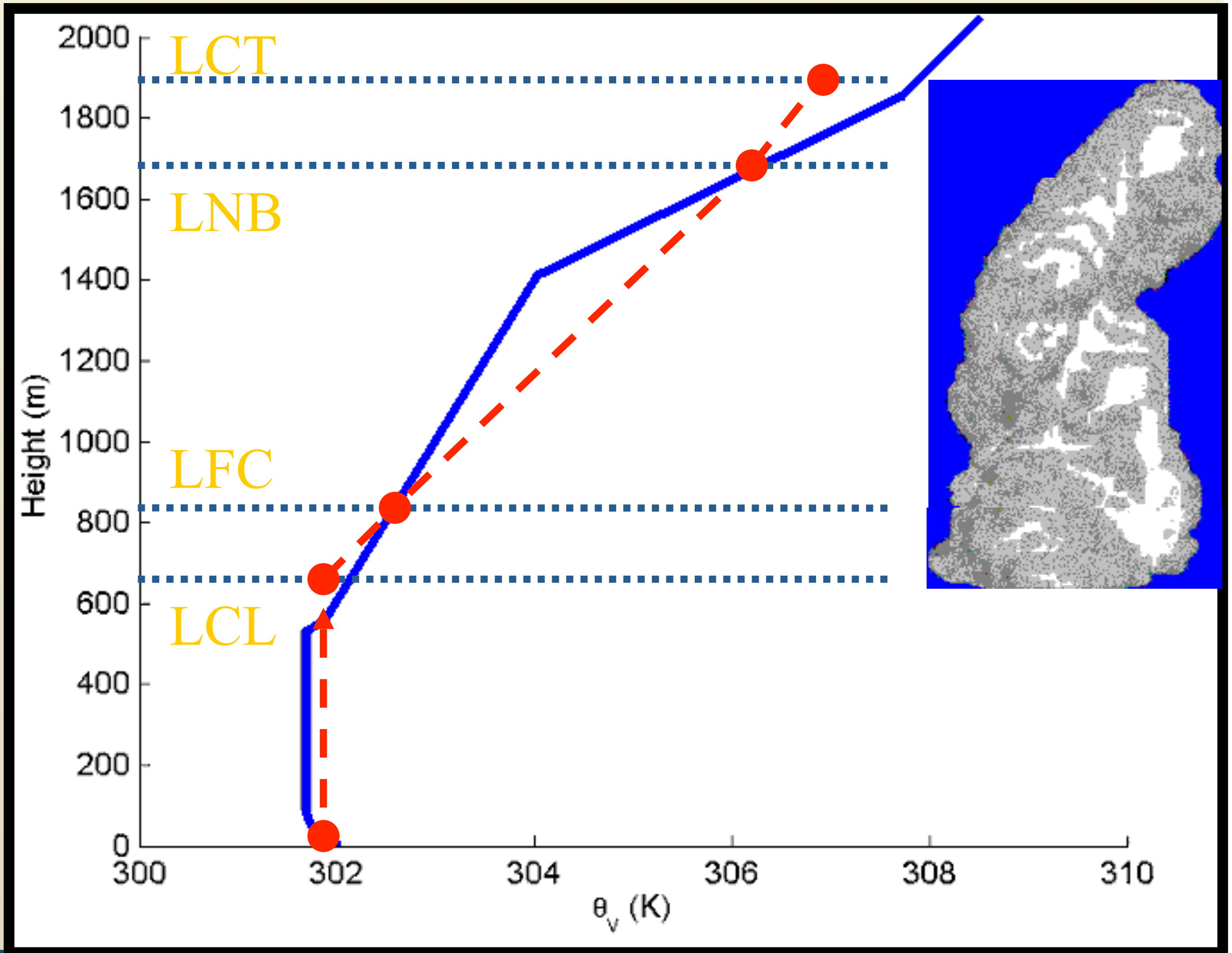
Outline

- Conceptual models of shallow cumulus clouds
- Results from Large Eddy Simulation
- UW Shallow Cu scheme (Bretherton et. al 2004)

Adiabatic/Undilute cloud model

The Paradox

- Cumulus cloud-top is determined by the neutral buoyancy level of nearly undilute sub-cloud air.
- Cumulus clouds are highly dilute; the mass of a cumulus cloud is composed mostly of entrained air.
- Cumulus clouds are highly inhomogeneous, nearly undilute sub-cloud air is observed throughout all levels of cumulus clouds.



Entraining plume model

The Paradox

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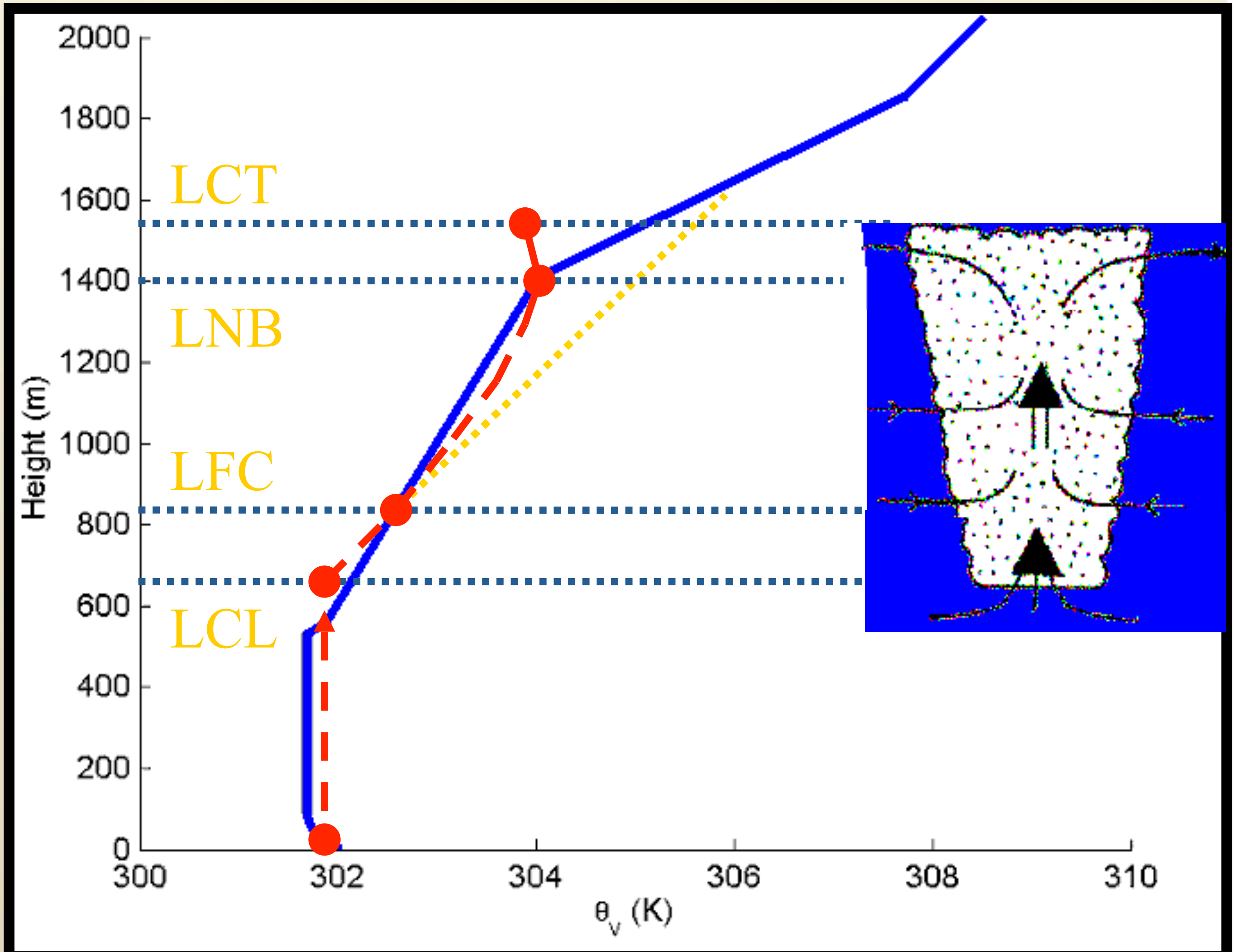

Episodic mixing and buoyancy-sorting model
(Raymond and Blyth 1986, Emanuel 1991, Zhao and Austin 2003)

The Paradox

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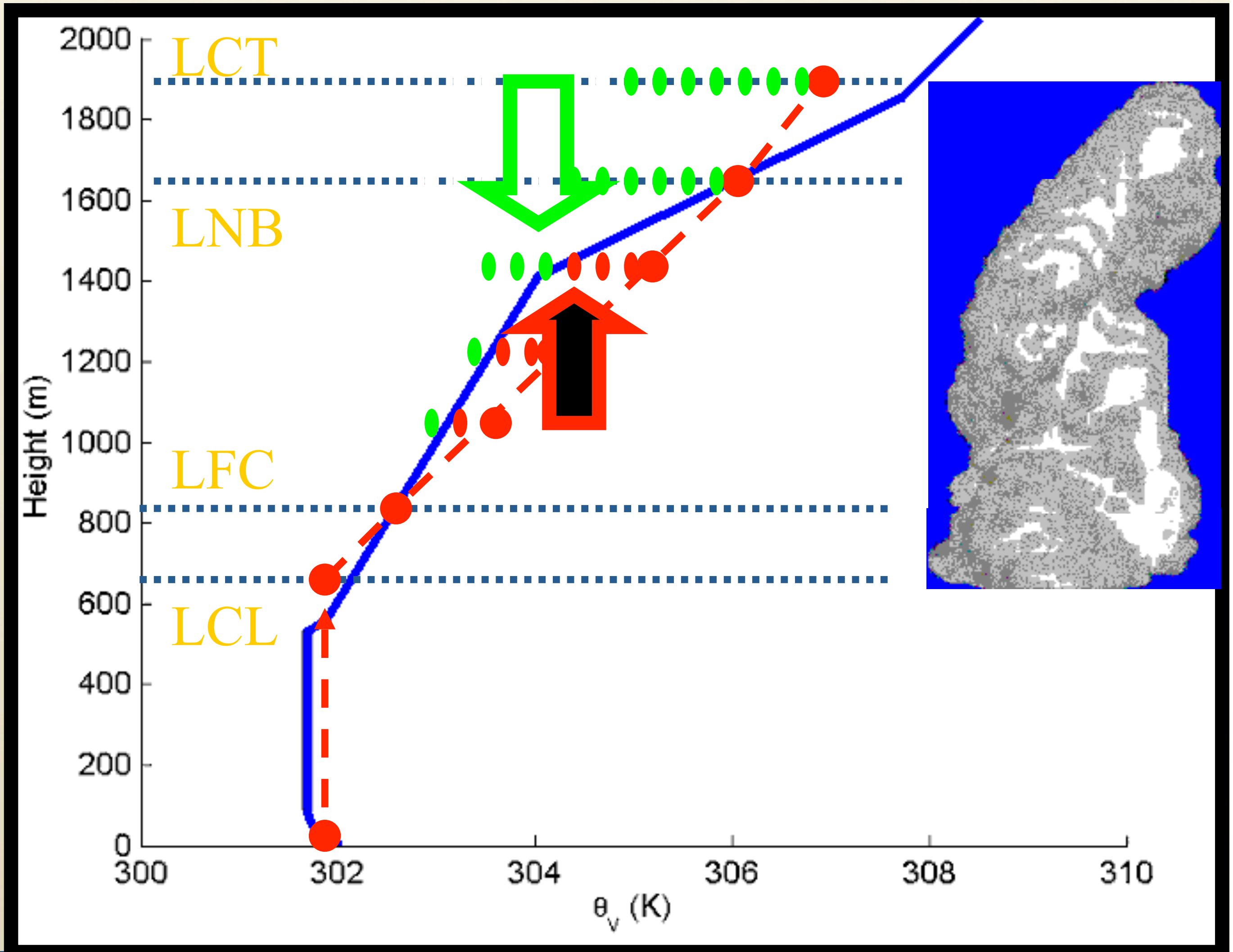
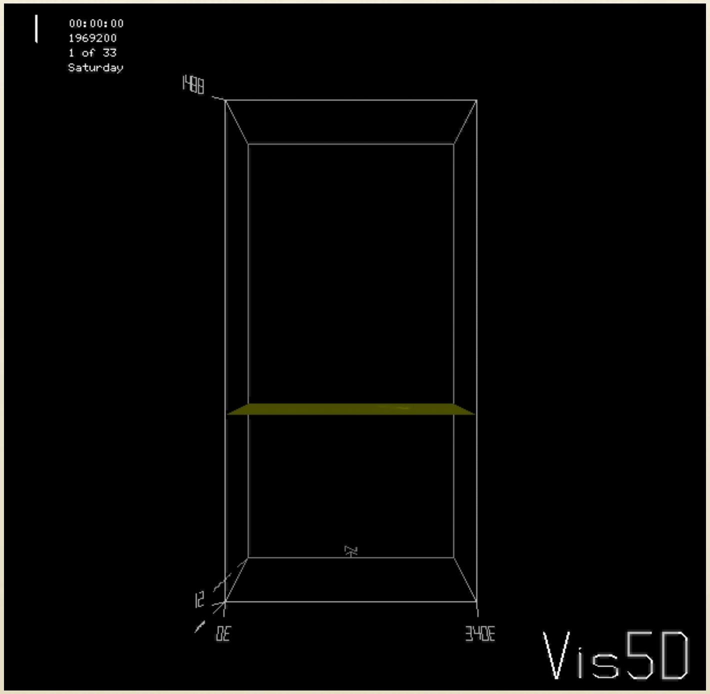
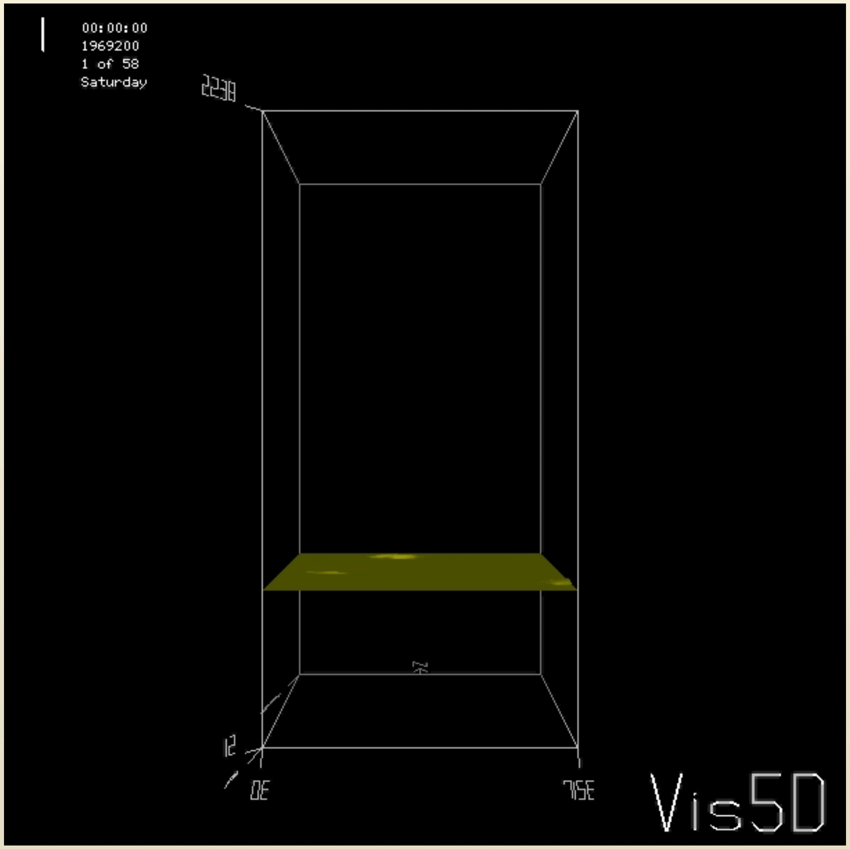


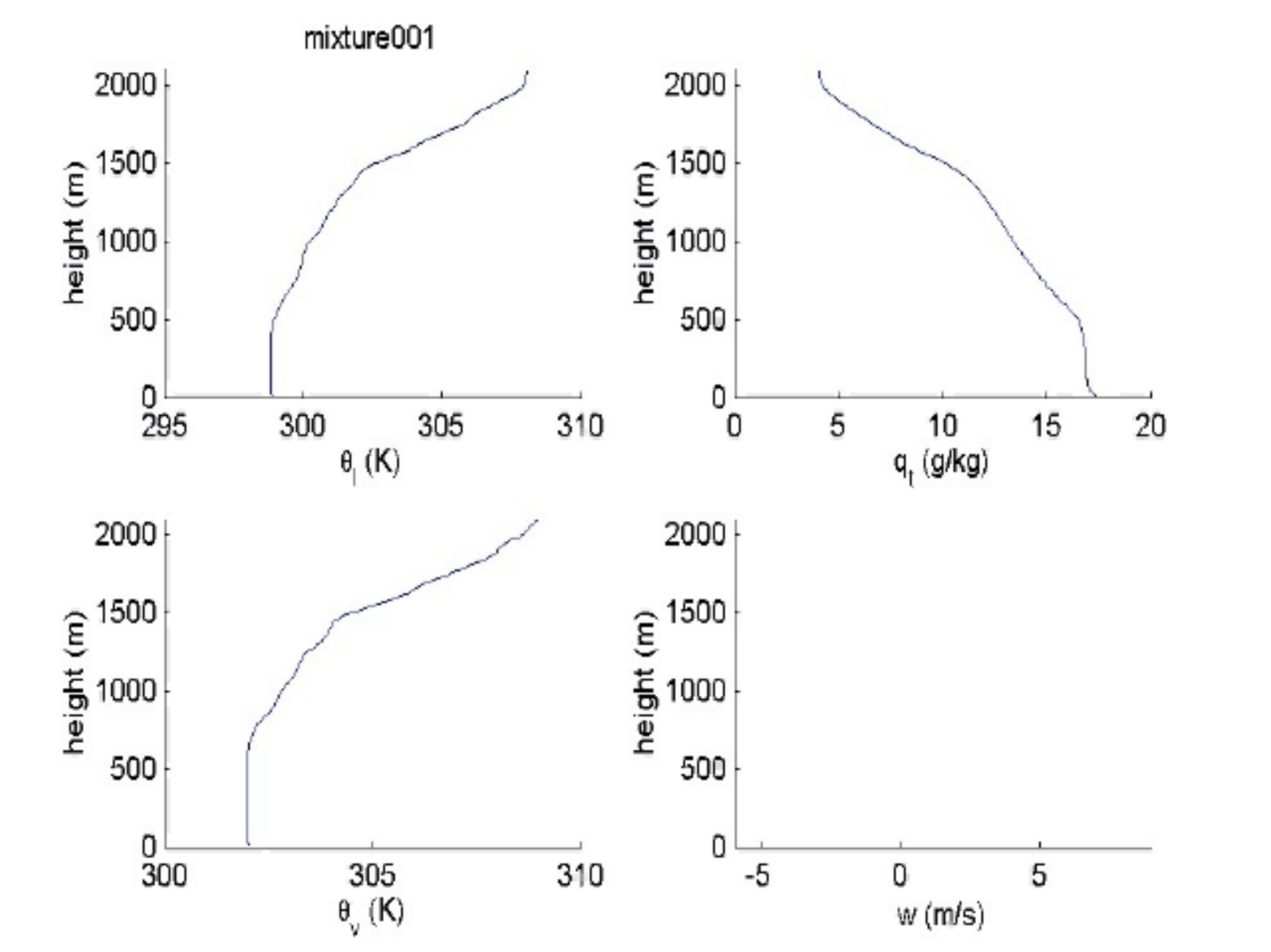
Animation of LES simulated shallow cumulus cloud life cycle
(Zhao and Austin 2005a,b)





Shallow Cu parameterization needs to account for the convective fluxes averaged over the cumulus ensemble which is at any time composed of a spectrum of clouds of different depths and different stages in their life-cycle.

Animation of LES simulated shallow cumulus cloud life cycle
(Zhao and Austin 2005a,b)



University of Washington - Shallow Cu Scheme
(Bretherton et. al 2004)

Cloud model:

- Single bulk entrainment-detrainment plume
- Buoyancy-sorting determination of entrainment/detrainment rate
- Explicit vertical momentum equation
- Cumulus cloud-top penetrative mixing

Closure:

- Cloud-base mass flux is determined by convective inhibition (CIN) and boundary layer TKE.

Bulk entraining-detraining plume model

$$\rho\overline{w'\psi'} \approx M_u(\psi_u - \overline{\psi})$$

supported by Siebesma and Cuijpers (1995)

$$M_u = \rho_u \sigma_u w_u$$

$$-\frac{\partial M_u}{\partial p} = E - D = \varepsilon M_u - \delta M_u, \qquad \varepsilon = \frac{\tilde{\varepsilon}}{\rho_u g}$$

$$-\frac{\partial M_u \psi_u}{\partial p} = E\overline{\psi} - D\psi_u + M_u S_\psi, \ \psi \in \left\{h_{lf}, q_t, u, v, w\right\}$$

$$-\frac{\partial \psi_u}{\partial p} = \varepsilon(\overline{\psi} - \psi_u) \quad + \quad S_\psi$$

$$\left(\frac{\partial \psi}{\partial t}\right)_{shcu} = g\frac{\partial M_u(\psi_u - \overline{\psi})}{\partial p} + gM_u S_\psi$$

$$= -gM_u \frac{\partial \overline{\psi}}{\partial p} + gD\left(\psi_u - \overline{\psi}\right)$$

$$h_{lf} = c_p T + gz - L_e q_c$$

$$q_t = q_v + q_c = q_v + q_l + q_i$$

$$q_s = q_s(T,p)$$

$$q_l = (1-\mu)q_c, \quad q_i = \mu q_c$$

$$\mu = f(T) = \max(\min(\frac{268 - T}{20}, 1), 0)$$

$$L_e = (1-\mu)L_v + \mu L_s$$

$$P_c = (q_c - q_{c,crit}), \qquad S_{q_c} = \frac{\Delta q_c}{\Delta p} = \frac{P_c}{\Delta p}$$

$$P_l = \frac{q_l}{q_c}P_c, \quad P_i = \frac{q_i}{q_c}P_c$$

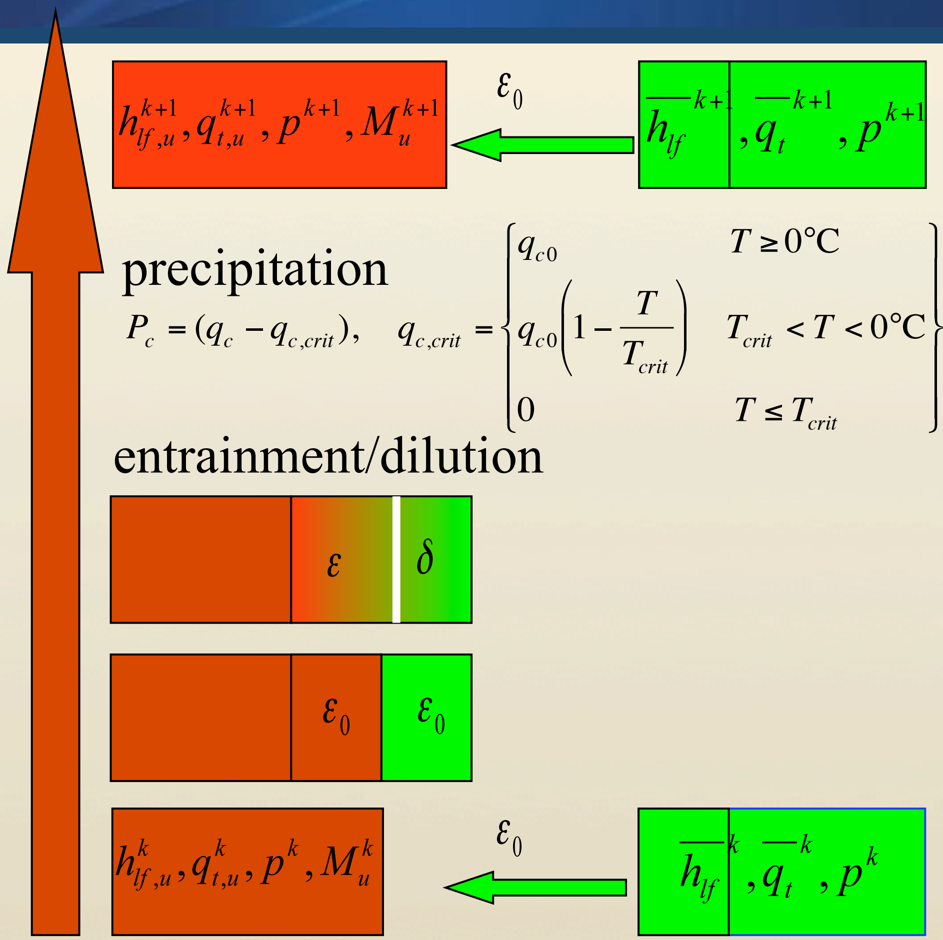
$$\left(\frac{\partial h_{lf}}{\partial t}\right)_{shcu} = g\frac{\partial M_u(h_{lf,u} - \overline{h_{lf}})}{\partial p} + gM_u\frac{P_c}{\Delta p}L_e$$

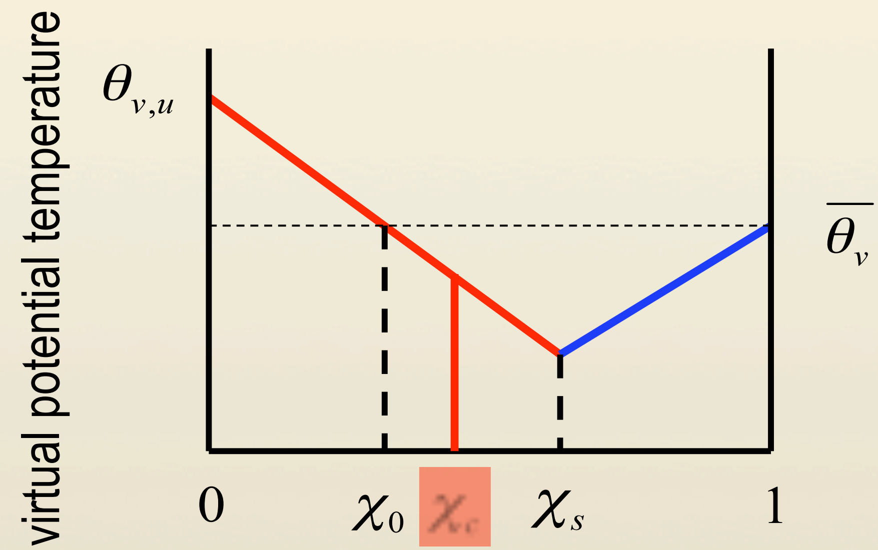
$$\left(\frac{\partial q_t}{\partial t}\right)_{shcu} = g\frac{\partial M_u(q_{t,u} - \overline{q_t})}{\partial p} - gM_u\frac{P_c}{\Delta p}$$

$$\left(\frac{\partial q_l}{\partial t}\right)_{shcu} = -gM_u\frac{\partial \overline{q_l}}{\partial p} + gD\left(q_{l,u} - \overline{q_l}\right)$$

$$\left(\frac{\partial q_i}{\partial t}\right)_{shcu} = -gM_u\frac{\partial \overline{q_i}}{\partial p} + gD\left(q_{i,u} - \overline{q_i}\right)$$

Lateral mixing, entrainment and detrainment





χ : fraction of environment air in mixtures

χ_c : maximum fraction of environment air for mixtures to be entrained

χ_s : maximum fraction of environment air for mixtures to be saturated

$$\varepsilon = 2\varepsilon_0 \int_0^{\chi_c} \chi \mathrm{PDF}(\chi) d\chi = \varepsilon_0 \chi_c^2$$

$$\delta = 2\varepsilon_0 \int_{\chi_c}^{1} (1-\chi) \mathrm{PDF}(\chi) d\chi = \varepsilon_0 (1-\chi_c)^2$$

$$\varepsilon_0 = \frac{c_0}{\rho g H} \text{(fractional lateral mixing rate)}$$

H : convective depth at previous timestep

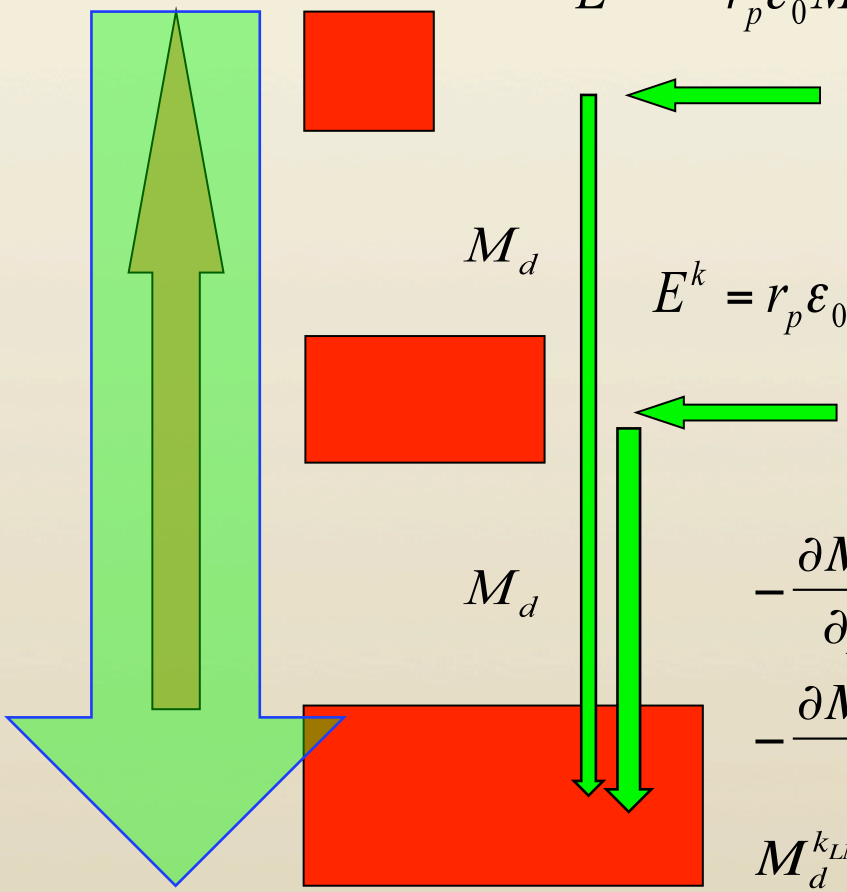
Plume vertical velocity equation

$$-\frac{1}{2}\frac{\partial w_u^2}{\partial p} = \frac{B_u}{\rho g} - \varepsilon w_u^2 - \beta, \qquad B_u = \left(g\,\frac{\theta_{v,u} - \overline{\theta_v}}{\overline{\theta_v}} \right)$$

β: drag due to pressure perturbation and growth of sub-plume turbulence
β: parameterized as linear combination of the first 2 terms (Simpson and Wiggert 1969)

$$-\frac{1}{2}\frac{\partial w_u^2}{\partial p} = \frac{aB_u}{\rho g} - b\varepsilon w_u^2$$

Cloud-top penetrative mixing



M_d

M_d

$$E^{ktop} = r_p \varepsilon_0 M_u^{ktop}$$

$$\overline{h_{lf}}^{ktop}, \overline{q_t}^{ktop}, p^{ktop}$$

cloud-top (Wu=0)

$$E^{k} = r_p \varepsilon_0 M_u^{k}$$

$$\overline{h_{lf}}^{k}, \overline{q_t}^{k}, p^{k}$$

penetrative entrainment

$$-\frac{\partial M_d}{\partial p} = E$$

$$-\frac{\partial M_d \psi_d}{\partial p} = E\overline{\psi}, \quad \psi \in \left\{ h_{lf}, q_t \right\}$$

$$M_d^{k_{LNB}-1/2} = 0$$

LNB (Bu=0)

Closure at cloud-base: Mb ~ exp (−CIN / TKE)

$$P(w) = \frac{1}{\sqrt{2\pi\sigma_w}}\exp\left(-\frac{w^2}{2\sigma_w}\right), \qquad \sigma_w = k_f e_{avg}$$

$$e_{avg} = \frac{1}{2}\left(u_*^3 + c_1 w_*^3\right)^{2/3}$$ **Holtslag and Boville (1993), J. Climate**

$$u_* = \left[\left(\overline{u'w'}\right)_s^2 + \left(\overline{v'w'}\right)_s^2\right]^{1/4}$$ **friction velocity scale**

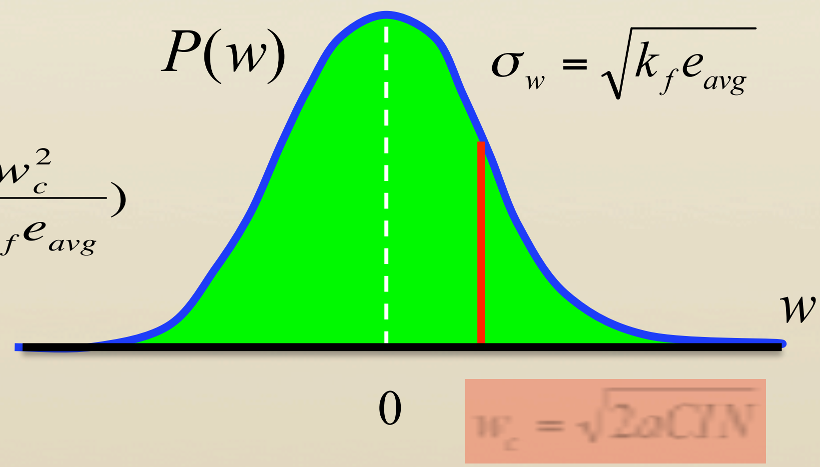
$$w_* = \left(\frac{g}{\theta_{v,s}}\left(\overline{w'\theta_v'}\right)_s h\right)^{1/3}$$ **convective velocity scale**

$$A_b = \int_{w_c}^{\infty} P(w)dw = \frac{1}{2}\mathrm{erfc}\left(\frac{w_c^2}{\sqrt{2k_f e_{avg}}}\right)$$

$$M_b = \overline{\rho}_b \int_{w_c}^{\infty} wP(w)dw = \overline{\rho}_b\sqrt{\frac{k_f e_{avg}}{2\pi}}\exp\left(-\frac{w_c^2}{2k_f e_{avg}}\right)$$

$$w_b = \frac{M_b}{\overline{\rho}_b A_b}$$

$$w_c = \max\left(\sqrt{2aCIN}, w_{c,\min}\right), w_{c,\min} = c_2\sigma_w$$



Flow chart of UW-ShCu

find source air property

↓

find LCL of source air

↓

calculation CIN

↓

determine CBMF

↓

set plume base level

↓

calculation plume properties

↓

cloud-top penetrative entrainment

↓

flux of heat/moisture/momentum

↓

tendencies to large-scale variables

Modules

Adiabatic cloud:
LCL, LFC, LNB, CIN, CAPE

CBMF closure:
PBL TKE / CIN based
alternative choices

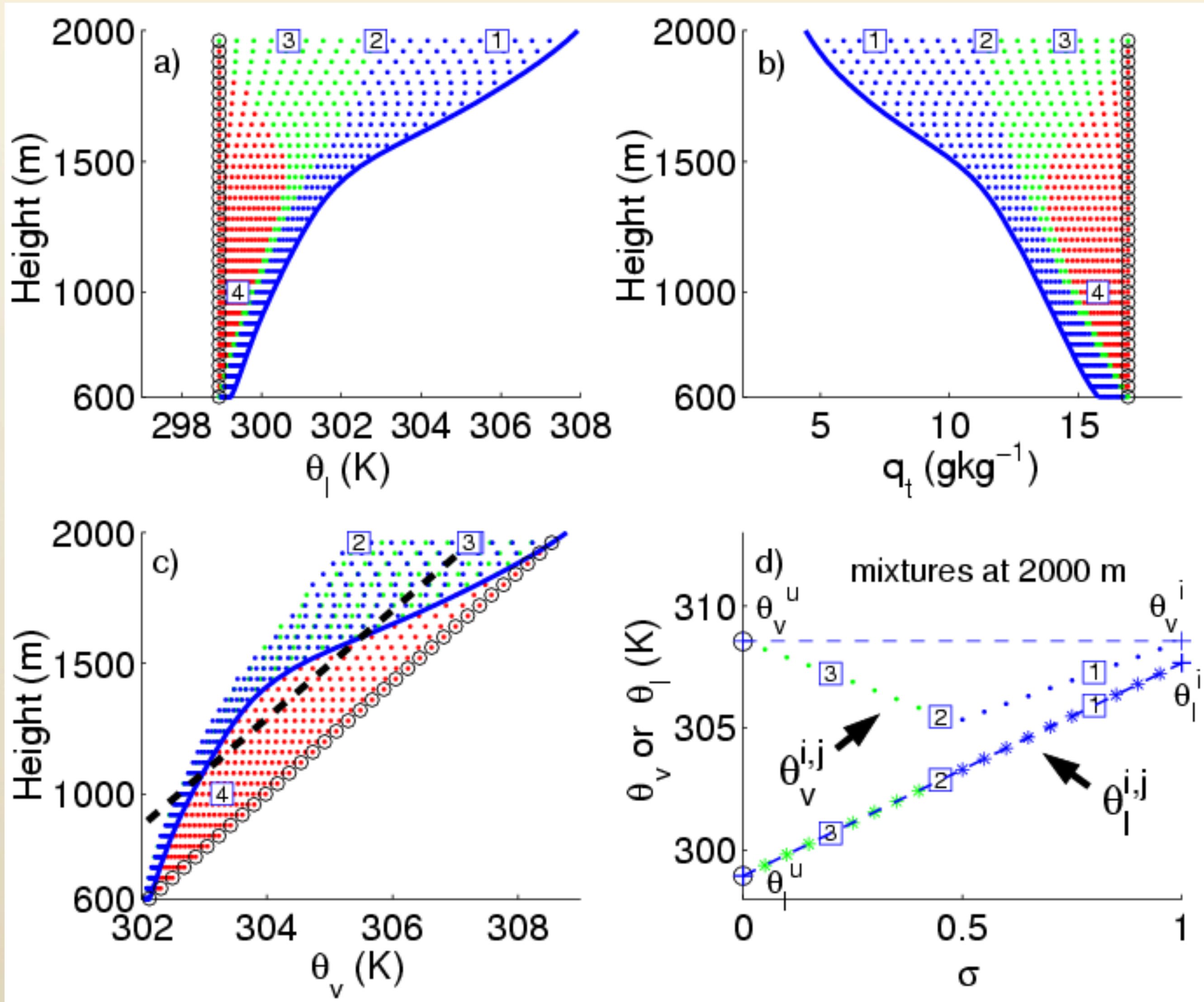
Plume model:
cumulus mixing assumptions
cloud microphysics assumptions
vertical velocity
cloud detrainment
cumulus penetrative mixing

Others:
source air determination
precipitation re-evaporation

End

Episodic mixing and buoyancy-sorting model
(Raymond and Blyth 1986, Emanuel 1991, Zhao and Austin 2003)

BOMEX case



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